How to Use Bitcoin to Play Decentralized Poker

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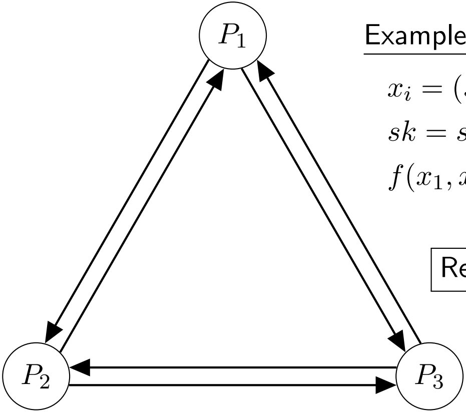
Secure multiparty computation (MPC) / secure function evaluation (SFE)

Parties $P_1, P_2, \ldots, P_n$ with inputs $x_1, x_2, \ldots, x_n$ send messages to each other, and wish to ***securely*** compute $f(x_1, x_2, \ldots, x_n)$.



Example of SFE:

$$x_i = (sk_i, c)$$

$$sk = sk_1 \oplus sk_2 \oplus \cdots \oplus sk_n$$

$$f(x_1, x_2, \ldots, x_n) = \texttt{decrypt}(sk, c)$$

Reactive MPC: think of poker cards

Impossibility of fair MPC

Fairness: if any party receives the output, then all honest parties must receive the output.

"Security with abort" is possible

- Secure MPC is possible [Yao86, GMW87, ...]
  - Security: correctness, privacy, independence of inputs, ~~fairness~~
  - Even with dishonest majority, in the computational setting.

Full security is impossible

- Fair MPC is impossible [Cle86]
  - r-round 2-party coin toss protocol is susceptible to $\Omega(1/r)$ bias.
  - $\Rightarrow$ no fair protocol for XOR, barring gradual release [...]

Our results

Outline of this presentation

1. Impose fairness for any SFE, without an honest majority.
2. Secure (reactive) MPC with money inputs and outputs.
   - Example: poker.

Formal model that incorporates coins

Functionality $\mathcal{F}_\square$ versus functionality $\mathcal{F}_\square^\star$ with coins

- If party P_i has (say) secret key sk_0 and sends it to party P_j, then both P_i and P_j will have the string sk_0.
- If party P_i has coins(x) and sends $y < x$ coins to party P_j, then P_i will have coins$(x - y)$ and P_j will have extra coins(y).

- With Bitcoin: the parties only send strings, but miners do PoW so that the coin transfers become irreversible.

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- With Bitcoin: the parties only send strings, but miners do PoW so that the coin transfers become irreversible.
- Ideally, all the parties deem coins to be valuable assets.
- Sending coins(x) may require a broadcast that reveals at least the amount x (maybe not in ZK cryptocurrency like Zerocash).
- It is possible to define a "secure computation with coins" model directly, or by using (UC) ideal functionalities.
- We provide simulation based proofs (but not in this talk).

Claim-or-Refund for two parties P_s,P_r (implicit in [Max11],[BBSU12])

The $\mathcal{F}^{\star}_{\mathrm{CR}}$ Claim-or-Refund ideal functionality

1. The sender P_s deposits (locks) her coins(q) while specifying a time bound τ and a circuit $\phi(\cdot)$.
2. The receiver P_r can claim (gain possession) of the coins(q) by publicly revealing a witness w that satisfies $\phi(w) = 1$.
3. If P_r didn't claim within time τ, coins(q) are refunded to P_s.

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How to realize $\mathcal{F}^{\star}_{\mathrm{CR}}$ via Bitcoin

- Old version: using "timelock" transactions.
- New version: `OP_CHECKLOCKTIMEVERIFY` (abbrv. `CLTV`) enables $\mathcal{F}^{\star}_{\mathrm{CR}}$ directly, avoiding transaction malleability attacks.

$\mathcal{F}^{\star}_{\mathrm{CR}}$ via Bitcoin (without `CLTV`)

High-level description the $\mathcal{F}^{\star}_{\mathrm{CR}}$ implementation in Bitcoin

- P_s controls TX_{old} that resides on the blockchain.
- P_s creates a transaction TX_{new} that spends TX_{old} to a Bitcoin script that can be redeemed by P_s and P_r, or only by P_r by supplying a witness w that satisfies $\phi(w) = 1$.
- P_s asks P_r to sign a timelock transaction that refunds TX_{new} to P_s at time τ (conditioned upon both P_s and P_r signing).
- After P_r signs the refund, P_s can safely broadcast TX_{new}.

1. P_s is safe because P_r only sees Hash(TX_{new}), and therefore cannot broadcast TX_{new} to cause P_s to lose the coins.
2. P_r can safely sign the random-looking data Hash(TX_{new}) because the protocol uses a freshly generated (sk_R, pk_R) pair.

The structure of Bitcoin transactions

How standard Bitcoin transactions are chained

- TX_{old} = earlier TX output of coins(q) is redeemable by pk_A
- $id_{\text{old}} = \text{Hash}(TX_{\text{old}})$
- $PREPARE_{\text{new}} = (id_{\text{old}}, q, pk_B, 0)$ 0 means no timelock
- $TX_{\text{new}} = (PREPARE_{\text{new}}, \ \texttt{Sign}_{sk_A}(PREPARE_{\text{new}}))$
- $id_{\text{new}} = \text{Hash}(TX_{\text{new}})$
- Initial minting transaction specifies some pk_M that belongs to a miner, and is created via *proof of work*.

Realization of $\mathcal{F}^{\star}_{\mathrm{CR}}$ via Bitcoin (without CLTV)

The $\mathcal{F}^{\star}_{\mathrm{CR}}$ transaction

- $PREPARE_{\textsf{new}} = (id_{\textsf{old}}, q, (pk_S \wedge pk_R) \vee (\phi(\cdot) \wedge pk_R), 0)$
- $\phi(\cdot)$ can be $\texttt{SHA256}(\cdot) == Y$ where Y is hardcoded.
- $TX_{\textsf{new}} = (PREPARE_{\textsf{new}},\ \texttt{Sign}_{sk_S}(PREPARE_{\textsf{new}}))$
- $id_{\textsf{new}} = \textsf{Hash}(TX_{\textsf{new}})$
- P_s sends $PREPARE_{\textsf{refund}} = (id_{\textsf{new}}, q, pk_S, \tau)$ to P_r
- P_r sends $\sigma_R = \texttt{Sign}_{sk_R}(PREPARE_{\textsf{refund}})$ to P_s
- P_s broadcasts $TX_{\textsf{new}}$ to the Bitcoin network
- If P_r doesn't reveal w until time τ then P_s creates $TX_{\textsf{refund}} = (PREPARE_{\textsf{refund}},\ (\texttt{Sign}_{sk_S}(PREPARE_{\textsf{refund}}), \sigma_R))$ and broadcasts it to reclaim her q coins

$\mathcal{F}^{\star}_{\text{CR}}$ via Bitcoin with CLTV (operational since $\approx$ December 2015)

Pseudocode: pk_S, pk_R, h_0, τ are hardcoded

`if (block# >` τ`) then`
  P_s `can spend the` coins(q) `by signing with` sk_s
`else`
  P_r `can spend the` coins(q) `by`
    `signing with` sk_r
    `AND`
    `supplying` w `such that` Hash$(w) = h_0$ ← `this is` $\phi(\cdot)$

Bitcoin script

```
IF <timeout> CHECKLOCKTIMEVERIFY
   HASH256 <h_0> EQUALVERIFY <pk_r> CHECKSIGVERIFY
ELSE
   <pk_s> CHECKSIGVERIFY
ENDIF
```

Fairness with penalties

Definition of fair secure multiparty computation with penalties

- An honest party never has to pay any penalty
- If a party aborts after learning the output and doesn't deliver output to honest parties $\Rightarrow$ every honest party is compensated

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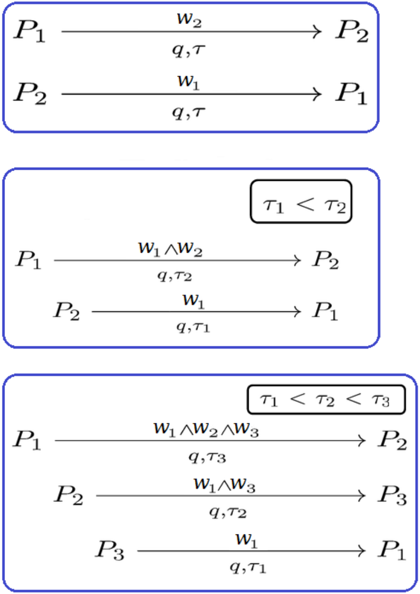
Outline of $\mathcal{F}_f^\star$ – fairness with penalties for any function f

- $P_1, \ldots, P_n$ with $x_1, \ldots, x_n$ run secure *unfair* SFE for f that
  1. Computes additive shares $(y_1, \ldots, y_n)$ of $y = f(x_1, \ldots, x_n)$
  2. Computes $\mathrm{Tags} = (\mathsf{com}(y_1), \ldots, \mathsf{com}(y_n))$ $= (\mathtt{hash}(y_1), \ldots, \mathtt{hash}(y_n))$
  3. Delivers (y_i, Tags) to every P_i
- $P_1, \ldots, P_n$ deposit coins and run fair reconstruction (fair exchange) with penalties to swap the y_i's among themselves.

Fair exchange in the $\mathcal{F}^{\star}_{\mathrm{CR}}$-hybrid model - the ladder construction

"Abort" attack:

P_2 claims without deposting



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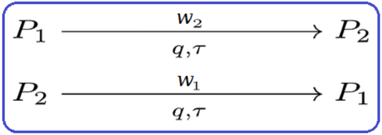
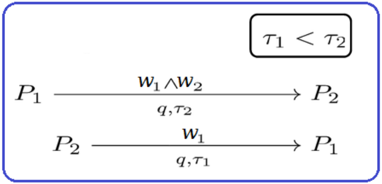
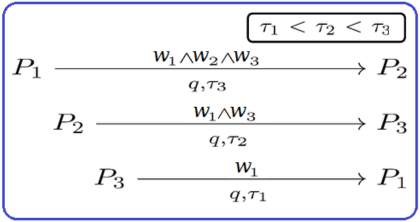


Fair exchange:

P_1 claims by revealing w_1

$\Rightarrow$ P_2 can claim by revealing w_2





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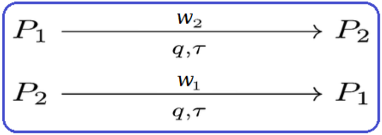

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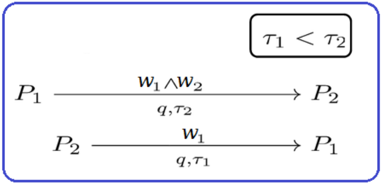
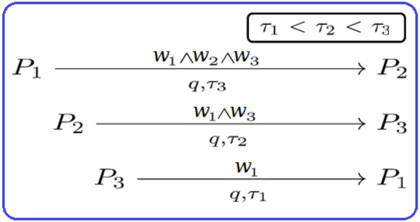


Malicious coalition:

Coalition P_1, P_2 obtain w_3 from P_3

P_2 doesn't claim the top transaction

P_3 isn't compensated



Fair exchange in the $\mathcal{F}^{\star}_{\mathrm{CR}}$-hybrid model - the ladder construction (contd.)

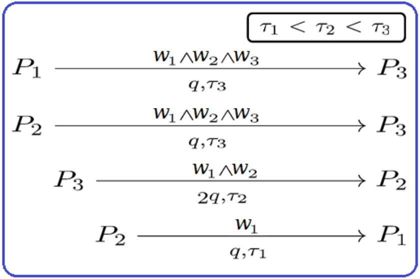
Fair exchange:

Bottom two levels:

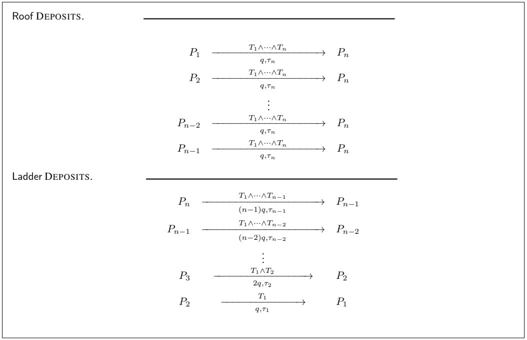
P_1, P_2 get compensated by P_3

Top two levels:

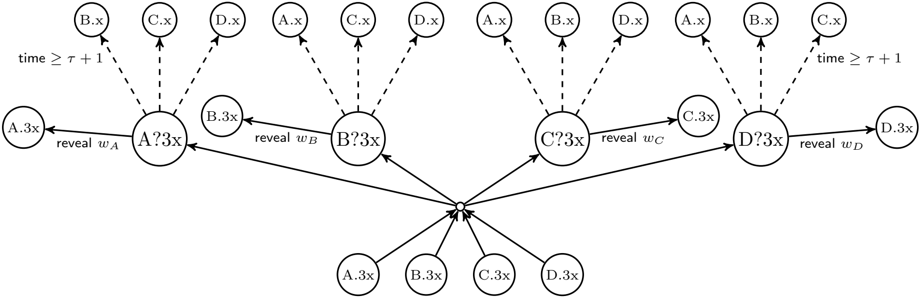
P_3 gets her refunds by revealing w_3



Full ladder:



Multilock



In principle, jointly locking coins for fair exchange can work well:

1. $M =$ "if P_1, P_2, P_3, P_4 sign this message with inputs of coins$(3x)$ each then their $3x$ coins are locked into 4 outputs of coins$(3x)$ each, where each P_i can redeem output T_i with a witness w_i that satisfies ϕ_i, and after time τ anyone can divide an unredeemed output T_i equally to $\{P_1, P_2, P_3, P_4\} \setminus \{P_i\}$"
2. P_1, P_2, P_3, P_4 sign M and broadcast it, and after M is confirmed, each P_i redeems coins(x) by revealing w_i

Practicality of multiparty fair exchange with penalties in Bitcoin

- Unfortunately, $\mathcal{F}^{\star}_{\mathrm{ML}}$ cannot be implemented in vanilla Bitcoin because of self-imposed “transaction malleability” (ECDSA is a randomized signature algorithm).
- Instead, we propose a protocol enhancement that eliminates transaction malleability while retaining expressibility.

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Recap:

- $\mathcal{F}^{\star}_{\mathrm{ML}}$ requires $O(1)$ Bitcoin rounds and $O(n^2)$ transaction data (and $O(n^2)$ signature operations), while the ladder requires $O(n)$ Bitcoin rounds and $O(n)$ transactions.
- Multiparty fair computation can be implemented in Bitcoin via the ladder construction.
- Multiparty fair computation can be implemented via $\mathcal{F}^{\star}_{\mathrm{ML}}$ with an enhanced Bitcoin protocol.

Comparison with other ways to achieve fairness

Gradual release

- Release the output bit by bit...
- Even with only 2 parties, the number of rounds depends on a security parameter.
- Complexity blowup because the protocol must ensure that the parties don't release junk bits.
- Assumptions on the computational power of the parties, sequential puzzles to avoid parallelization.

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Trusted bank

- Legally Enforceable Fairness [Lindell 2008]
- Requires a trusted party to provide an ideal bank functionality.
- 2-party only: the bank can provide $\mathcal{F}^{\star}_{\mathrm{CR}}$ or $\mathcal{F}^{\star}_{\mathrm{ML}}$ to use our constructions directly, or implement similar protocols.
- Not a secure cash distribution protocol...

Secure cash distribution and poker

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"Paradoxical" Abilities 1983-

- Exchanging Secret Messages without Ever Meeting
- Simultaneous Contract Signing Over the Phone
- Generating exponentially long pseudo random strings indistinguishable from random
- Proving a theorem without revealing the proof
- $\Longrightarrow$ Playing any digital game without referees
- Private Information Retrieval

Secure cash distribution with penalties

Ideal 2-party secure (non-reactive) cash distribution functionality:

1. Wait to receive $(x_1, \text{coins}(d_1))$ from P_1 and $(x_2, \text{coins}(d_2))$ from P_2.
2. Compute $(y, v) \leftarrow f(x_1, x_2, d_1, d_2)$.
3. Send $(y, \text{coins}(v))$ to P_1 and $(y, \text{coins}(d_1 + d_2 - v))$ to P_2.

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- In the general case, each party P_i has input $(x_i, \text{coins}(d_i))$ and receives output $(y, \text{coins}(v_i))$.
- Use-cases: generalized lottery, incentivized computation, . . .

Blackbox secure cash distribution

- Blackbox realization of secure cash distribution in the $\mathcal{F}^{\star}_{\mathrm{CR}}$-hybrid model.
- Assume: the input coins amount of P_i is an m_i-bit number.

Step 1: commit to random secrets (preprocessing)

For all $i \in [n], j \in [n] \setminus \{i\}, k \in [m_i]$:

- P_i picks a random witness $w_{i,j,k} \leftarrow \{0,1\}^\lambda$
- P_i computes $c_{i,j,k} \leftarrow \mathsf{commit}(1^\lambda, w_{i,j,k})$.
- P_i sends $c_{i,j,k}$ to all parties.
- P_i makes an $\mathcal{F}^{\star}_{\mathrm{CR}}$ transaction $P_i \xrightarrow[2^k,\tau]{w_{i,j,k}} P_j$

Blackbox secure cash distribution (contd.)

Denote the the input coin amounts by $d = (d_1, \ldots, d_n)$ and the string inputs by $(x_1, x_2, \ldots, x_n)$.

Step 2: compute the cash distribution

Invoke secure SFE (unfair for now) for the cash distribution:

- Compute the output coin amounts $v = (v_1, v_2, \ldots, v_n)$.
- Derive numbers $b_{i,j}$ that specify how many coins P_i needs to send P_j according to the input coins d and output coins v.
- Let $(b_{i,j,1}, b_{i,j,2}, \ldots, b_{i,j,m_i})$ be the binary expansion of $b_{i,j}$.
- For all i, j, k, if $b_{i,j,k} = 1$ then concatenate to the output a value $w'_{i,j,k}$ that satisfies commit$(1^\lambda, w'_{i,j,k}) = c_{i,j,k}$.
- Compute $y = f(x_1, x_2, \ldots, x_n)$ and output y too.

Then, use fair exchange with penalties (with time limit $< \tau$) to deliver the output to all parties, so that $\mathcal{F}^\star_{\mathrm{CR}}$ claims will ensue.

Is one-shot protocol enough?

Are we there yet?

Is one-shot protocol enough?

Are we there yet? In the case of poker, not really.

- The most natural formulation of poker is as a *reactive* secure MPC.
- Multistage protocol: after each stage of the computation some intermediate outputs are revealed to the parties.
  - Example: the top card of the deck is revealed to all parties.
- One-shot protocol is not the natural formulation:
  - A circuit that takes into account all the possible variables is highly inefficient.
  - Those variables may depend on external events (say, you receive a phone call regarding an unrelated financial loss).
- $\Rightarrow$ must be dropout-tolerant:
  - After a stage that reveals information, corrupt parties must be penalized if they abort.
  - In fact, the corrupt parties must be penalized unless they continue the next stage of the computation.

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Ingredients needed:

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- Blackbox secure cash distribution as described, with refunds at time τ that exceeds the see-saw time limits, and hence with circuits specified at start that are utilized in the final rounds.

The see-saw construction: 2 parties

ROOF DEPOSIT.

$$P_1 \xrightarrow[q,\tau_{m,2}]{\mathrm{TT}_{m,2}} P_2 \qquad (\mathsf{Tx}_{m,2})$$

SEE-SAW DEPOSITS. For $r = m - 1$ to 1:

$$P_2 \xrightarrow[2q,\tau_{r+1,1}]{\mathrm{TT}_{r+1,1}} P_1 \qquad (\mathsf{Tx}_{r+1,1})$$

$$P_1 \xrightarrow[2q,\tau_{r,2}]{\mathrm{TT}_{r,2}} P_2 \qquad (\mathsf{Tx}_{r,2})$$

FLOOR DEPOSIT.

$$P_2 \xrightarrow[q,\tau_{1,1}]{\mathrm{TT}_{1,1}} P_1 \qquad (\mathsf{Tx}_{1,1})$$

The see-saw construction: multiparty

Roof deposits. For each $j \in [n-1]$:

$$P_j \xrightarrow[q,\tau_{2n-2}]{\mathrm{TT}_n} P_n$$

Ladder deposits. For $i = n-1$ down to 2:

- Rung unlock: For $j = n$ down to $i+1$:

$$P_j \xrightarrow[q,\tau_{2i-1}]{\mathrm{TT}_i \wedge U_{i,j}} P_i$$

- Rung climb:

$$P_{i+1} \xrightarrow[i \cdot q,\tau_{2i-2}]{\mathrm{TT}_i} P_i$$

- Rung lock: For each $j = n$ down to $i+1$:

$$P_i \xrightarrow[q,\tau_{2i-2}]{\mathrm{TT}_{i-1} \wedge U_{i,j}} P_j$$

Foot deposit.

$$P_2 \xrightarrow[q,\tau_1]{\mathrm{TT}_1} P_1$$

The see-saw construction: multiparty (contd.)

Properties of the multiparty see-saw

- With m rounds, $O(n^2m)$ calls to $\mathcal{F}^{\star}_{\mathrm{CR}}$ (ladder is $O(nm)$).
- $O(nm)$ security deposit by each party.

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  - Consider poker: suppose that in round j all parties exchange shares to reveal the top card of the deck.
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- The circuits verify a signed extension of the entire execution transcript, and that this extension conforms with the protocol.
- $\Rightarrow$ needs more expressive scripting language than vanilla Bitcoin, but not Turing complete scripts because the round bounds are known in advance.

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- Preprocessing step: make the cash distribution transactions with random circuits $w_{i,j,k}$.
- Invoke (preprocess) at start an unfair SFE that:
  - Shuffles the deck according to the parties' random inputs.
  - Computes commitments to shares of all the cards.
  - Deals shares of the hands and shares of the rest of the cards to all parties, and also delivers all the commitments to all parties.

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- The $\mathcal{F}^{\star}_{\mathrm{CR}}$ circuit in each round of the see-saw will verify signatures of a transcript, then enforce betting rules or force a party to reveal a share of a card, or in the final round force a party to reveal some $w_{i,j,k}$ values.
- For example: if all partied called and the top card on the deck should be revealed, then the next see-saw circuits will require each party to reveal her share of the top card.

Some open questions

- Lower bound of linear number of rounds for fairness with penalties in the $\mathcal{F}^{\star}_{\mathrm{CR}}$-hybrid model?
- Constructing secure cash distribution with penalties from *blackbox* secure MPC and $\mathcal{F}^{\star}_{\mathrm{CR}}$?

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version 4